◆ Outline

- Where are we and where are we going?
- Introduction to VLHC — the options and the issues
- High-field magnet R&D
- Some answers to the big questions

◆ Where are we now?

- The Tevatron is the world's highest energy machine, and has great frontier physics for the next 6–8 years.
- The LHC is being built at CERN. The U.S. is participating in the machine and the detectors.
- The world HEP community is searching for the right thing to do as the next step after the LHC.

  The choices as we see them now:

☞ NLC — $E_{collision} \sim 1$ TeV Question: Will 1 TeV be interesting?

☞ Muon Collider — $E_{collision} \sim 4$ TeV Question: Will it work?

☞ VLHC — $E_{collision} \sim 5 - 10$ TeV Question: Can we afford it?

The Real Question

- **Is LHC the end of the road for accelerator-based HEP?**
  - *When will we know where we want to go? (Via physics, not politics)*
  - *Can we risk starting the trip without the destination clearly in mind?*
  - *How do we pay for the ticket?*

- The Very Large Hadron Collider
  - *The Snowmass-96 VLHC*

    A 50 TeV x 50 TeV proton-proton collider

    Luminosity $\geq 10^{34}$ cm^{-2}s^{-1}

    Injection energy = 3 TeV ??

    Three colliders were studied, each with different magnetic field strengths:

    1.8 T 9.5 T 12.5 T

    The goal was (and still is) to develop a workable collider that is affordable.

Choosing the magnet strength

What are the magnet possibilities?

Low field	$B \leq 2$ T	Fermilab R&D
Moderate field	$4\ T < B < 9\ T$	Tevatron, UNK, HERA, RHIC, LHC
High field	$9\ T < B \leq 12\ T$	Fermilab R&D with LBL & KEK
Very high field	$B > 12$ T	BNL & LBNL R&D

- **Field strength choice is complicated by many issues:**

  Ring circumference
  Synchrotron radiation
  Accelerator physics issues
  Magnet costs; Total cost
  Superconducting materials choices
  Many more…

◆ Choosing the magnet strength

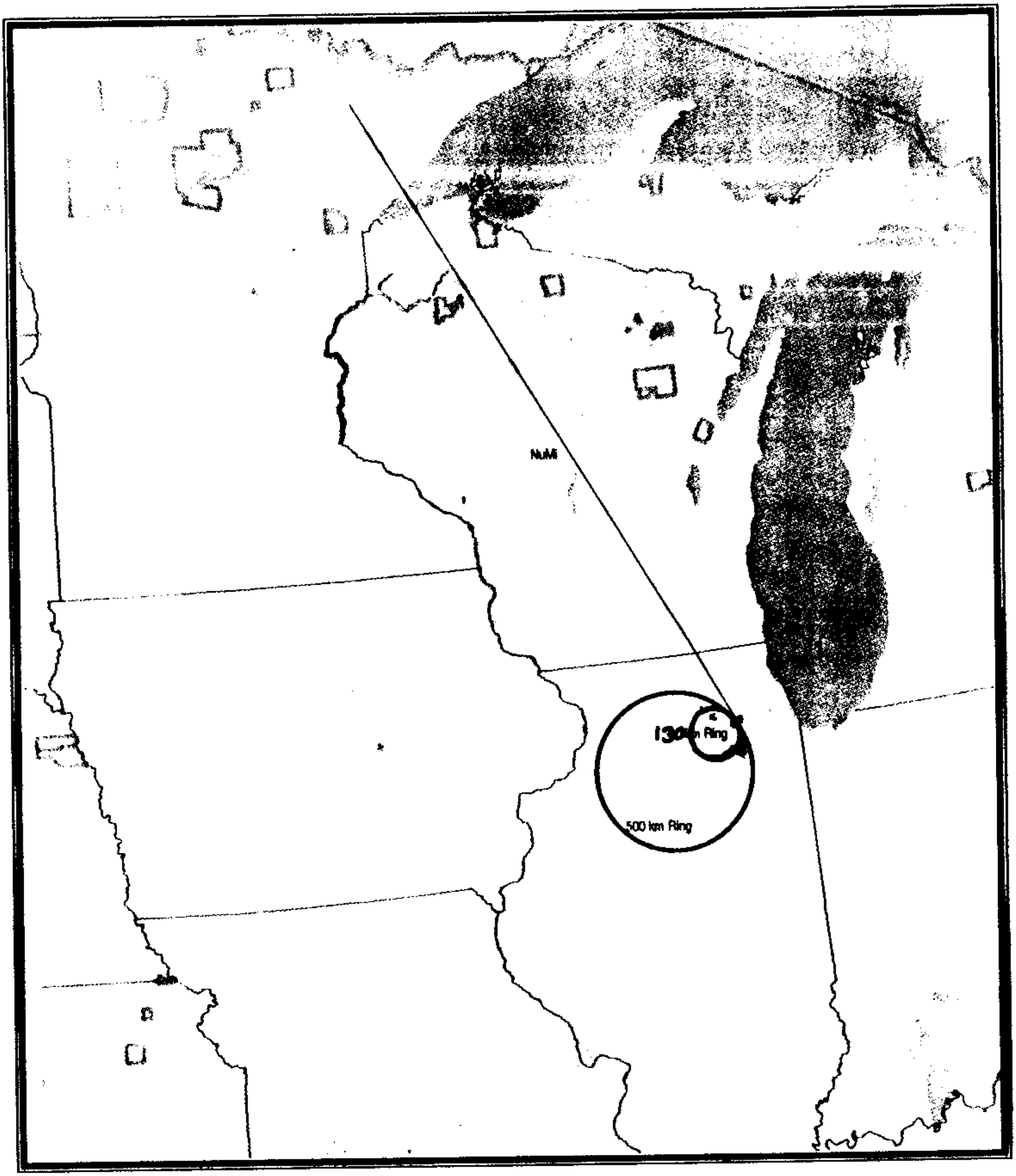
☞ For example — Ring size:

2 T Magnets → 500 km

10 T Magnets → 130 km

12.5 T Magnets → 104 km

500 km Pipetron Map Study



500 km Pipetron Map Study

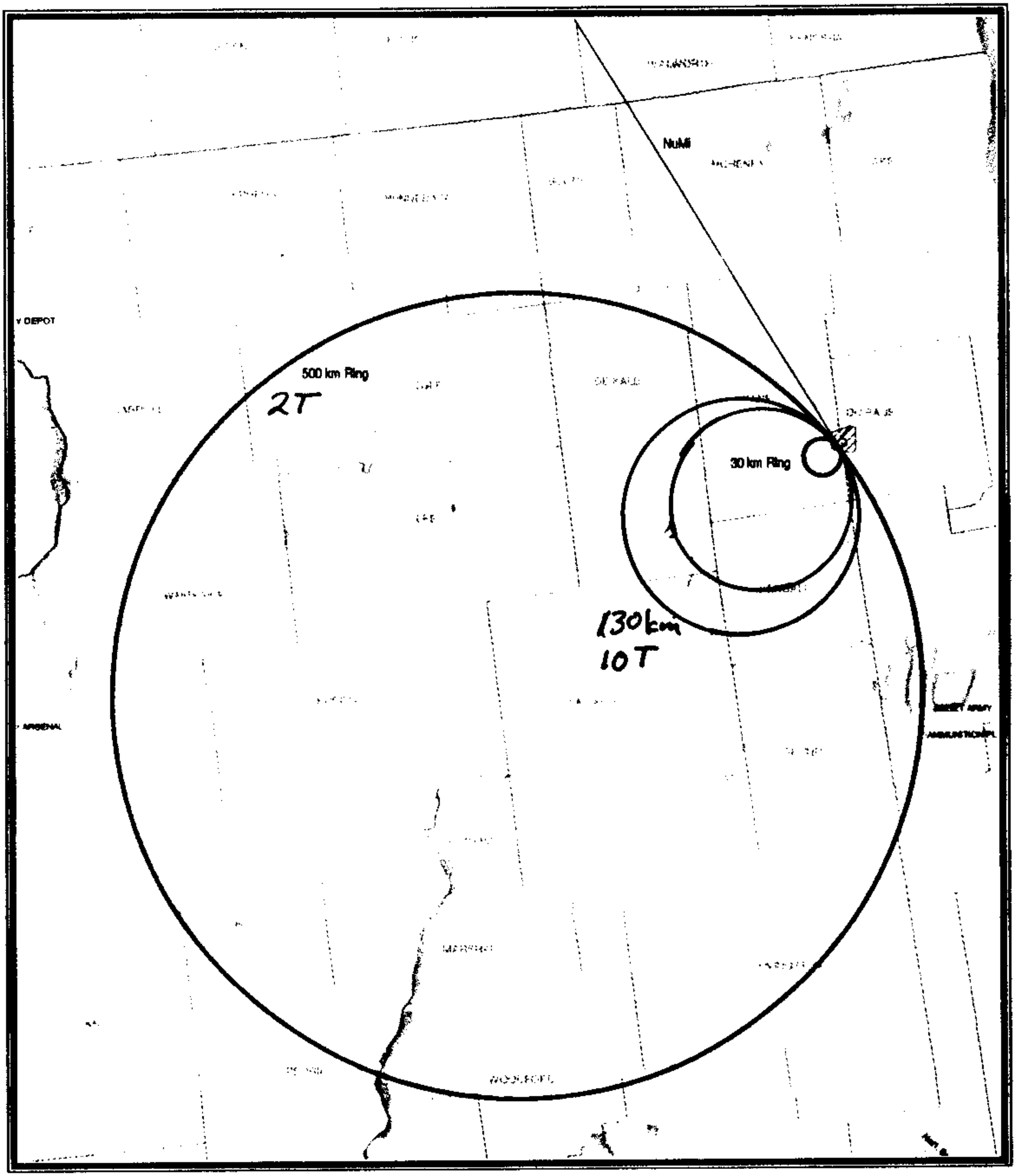


Table I : Machine parameters

Parameter	High field-new technology	High field-known technology	Low Field	Units
CM Energy	100	100	100	TeV
Dipole field	12.6	9.5	1.8	T
Circumference	104	138	646	km
Synchrotron radiation damping time (horizontal amplitude)	2.6	4.6	*antidamped*	hr
Initial/peak luminosity	.35/1.2	.35/1.0	1./1.	10^{34} cm^{-2}sec^{-1}
Integrated luminosity per day	500	500	700	pb^{-1}
Number of stores per day	2	2	1	
Initial rms normalized emittance	1.	1.	1.	π µm-rad
β^*	20	20	20	cm
Protons/bunch	0.5	0.5	0.94	10^{10}
Number of bunches	20794	27522	129240	
Equilibrium emittance (x)	144.2	62	1.8	10^{-3} π µm-rad
Bunch spacing	16.7	16.7	16.7	nsec
Beam stored energy	.89	1.18	9.73	GJ
Synchrotron radiation power/ring	189	143	48	kW
Total protons/ring	1.1	1.5	12.2	10^{14}
Initial/peak interactions/crossing	7.5/21.5	7.5/21.5	21.5/21.5	
Beam lifetime (pp collisions only)	34	45	130	hr
$\sigma_{inelastic}$	130	130	130	mbarn
Initial beam-beam $\Delta\nu$ (total)	5.1	5.1	11.6	10^{-3}
Revolution frequency	2.89	2.18	.46	kHz
Synchrotron frequency	8.9	5.8	.86	Hz
Rf Voltage	100	100	100	MV
Radio-frequency	360	360	360	MHz
Energy loss/turn	3678	2778	526	keV
Rms relative energy spread(collision)	15.6	18.0	39.0	10^{-6}
Fill time	16.3	16.3	28	min.
Acceleration time	5.8	7.6	35.9	min.
Total time: fill and accelerate	22.1	24	63.9	min.
Longitudinal impedance threshold: $\frac{Z_{\parallel}}{n}$(collision)	3.6	2.7	1.1	Ω
Transverse impedance threshold: $Z_{\perp}$(injection)	731	635	250	MΩ/m
Resistive-wall transverse impedance: $Z_{RW}(\frac{c}{\sigma_s})$ (injection)	0.4	0.5	98	MΩ/m
Resistive-wall multibunch instability growth time	472	310	.36	turns
Total current	.05	.05	.09	Amp
Peak current(inj)	3.6	3.6	4.2	Amp
$<\beta>$	255	255	382	m
Tune	65	86	269	
Half cell length (assumed 90^ocells)	200	200	300	m
Beam pipe radius	1.65	1.65	1.0	cm
Beam pipe	Cold, Cu	Cold, Cu	Warm, Al	

◆ *Dear, we need to talk about synchrotron radiation.*

- Synchrotron radiation is:

Bad: it puts power into the cryogenics & ruins the vacuum.

<u>Cryogenic load:</u> @ 50 TeV, 10 T

$W/turn = 8x10^{-3}\ E^4/\rho = 2x10^{-3}E^3B = 2.75$ MeV/turn

$P_{total} = IW = 0.1A \times 2.75$ MeV = 275 kw/beam = 550 kw total

For a shield at 80 K, this is about <u>6 MW</u> at the plug. **Not too bad!**

<u>Vacuum load:</u>

$P/meter = P_{total}/2\pi\rho = I \times 10^{-4}E^2B^2 = 2.6$ W/m Almost 10 times the LHC!

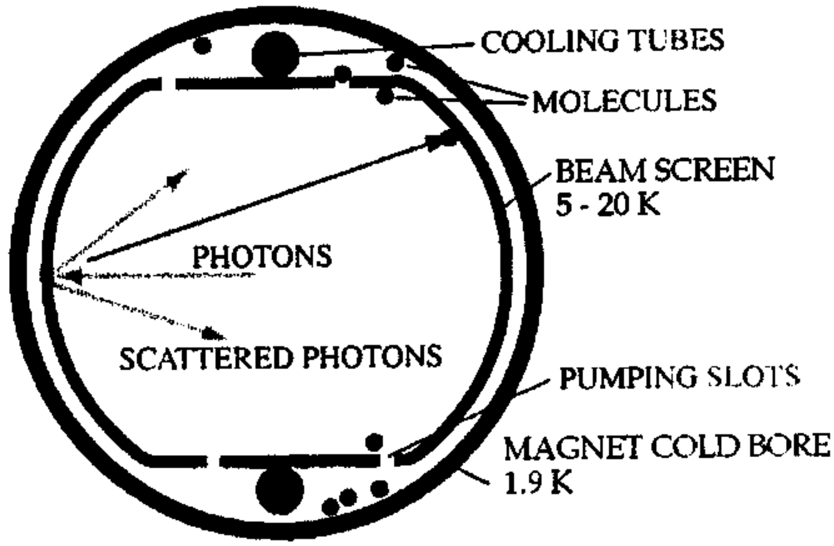
- Synchrotron radiation is:

Good: it makes the beam emittance (size) smaller.

$\tau_{damping} \propto 1/EB^2 \cong 4$ hrs (horiz) Beam size gets smaller
Luminosity increases!

LHC vacuum with synchrotron radiation.

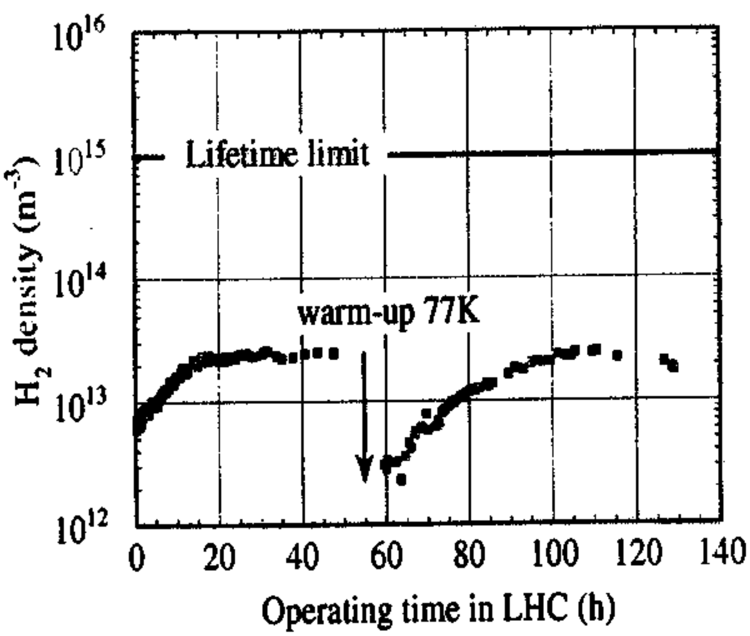
Synchrotron radiation photons desorb strongly bound gas molecules which are cryosorbed and gradually accumulate on the cold beam screen.



Scattered/reflected photons re-desorb these molecules at a rate increasing with coverage, leading in turn to an increasing gas density (pressure).

The increase in pressure due to 'recycling' of molecules increases the probability for gas to escape through the pumping slots and to be permanently cryosorbed on the 1.9K cold bore. This effect stabilises the gas density in the beam pipe to a safe value.

Without pumping holes, the beam screen would have to be warmed-up periodically to pump-out any condensed gas.



Test run at INP in Novosibirsk, scaled to LHC parameters and for initial operation at ~1/10 of the nominal beam current illustrating the effect of warming-up the beam screen.

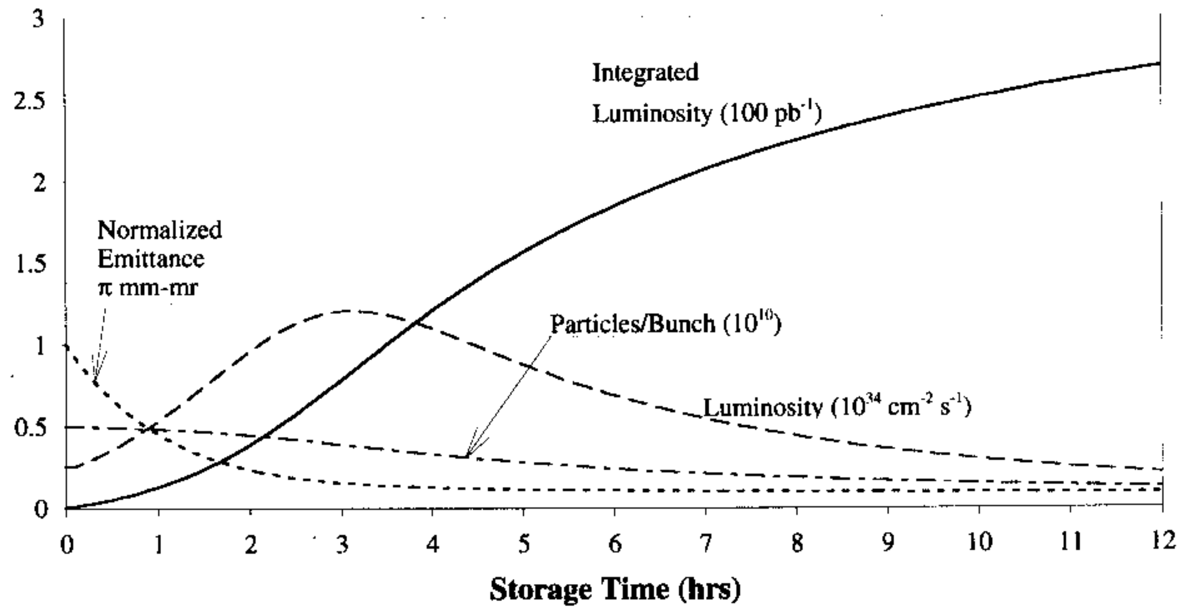


Fig. 3: Beam parameters during a store for high-field RLHC.

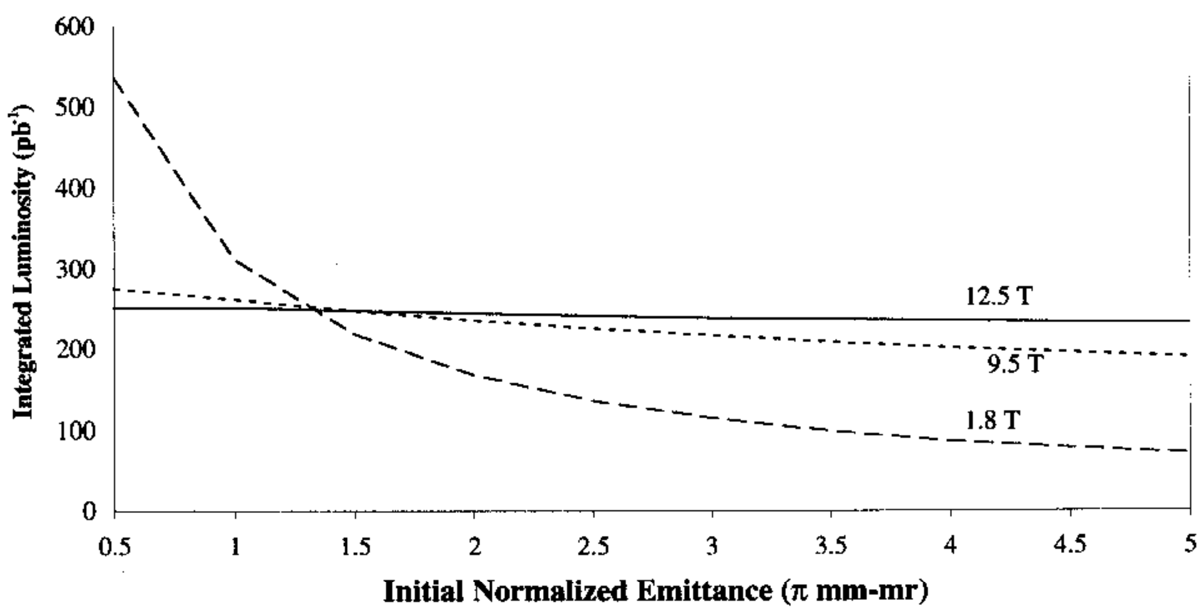
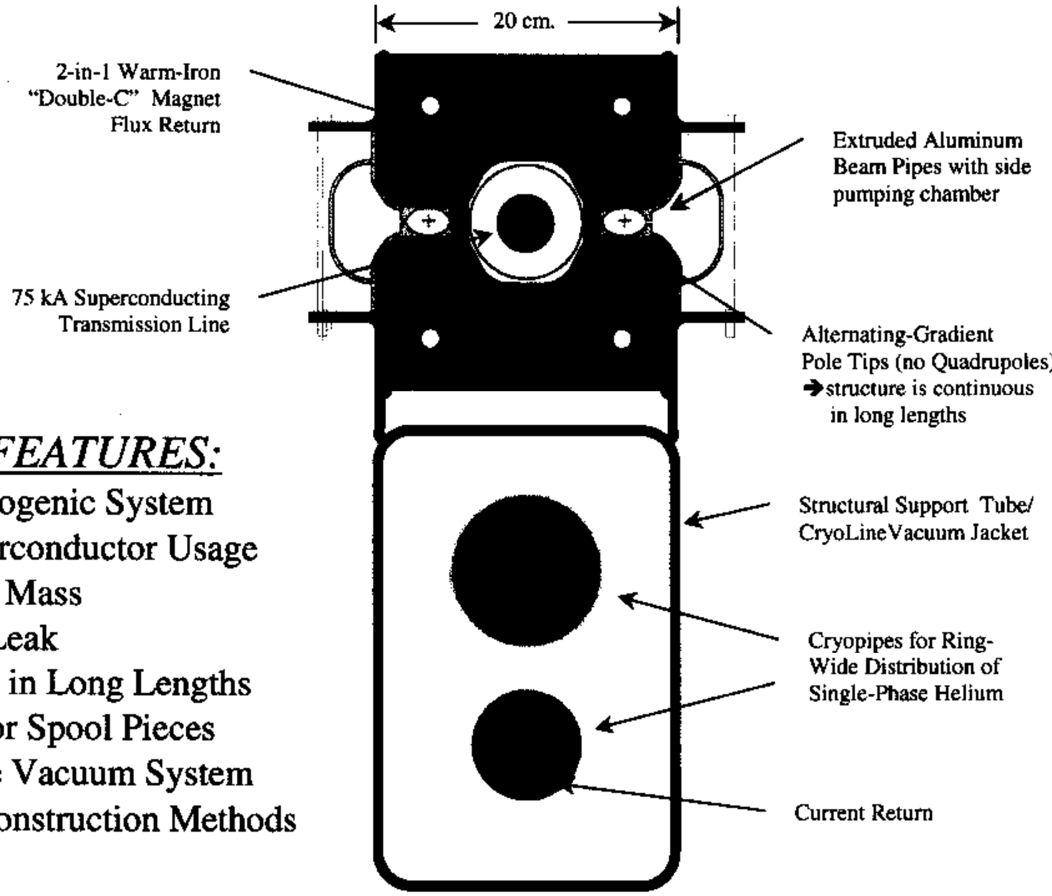


Fig. 4: Integrated luminosity of 10 hour store vs. initial rms emittance for RLHC options. The integrated luminosity of the two high-field cases is almost independent of the initial emittance because of synchrotron radiation damping.

◆ *Magnet Options for VLHC*

- ***Low-field magnets*** ***($B \leq 2$ T)***
  - **Uses superferric magnets**
    - **magnet is elegant and simple**
    - **the low-field magnet may be cheaper**
      (but it's the total cost that counts)
  - **There are some machine issues related to the large circumference**
  - **No synchrotron radiation damping**

Transmission Line Magnet



KEY FEATURES:

- Simple Cryogenic System
- Small Superconductor Usage
- Small Cold Mass
- Low Heat Leak
- Continuous in Long Lengths
- No Quads or Spool Pieces
- Warm Bore Vacuum System
- Standard Construction Methods

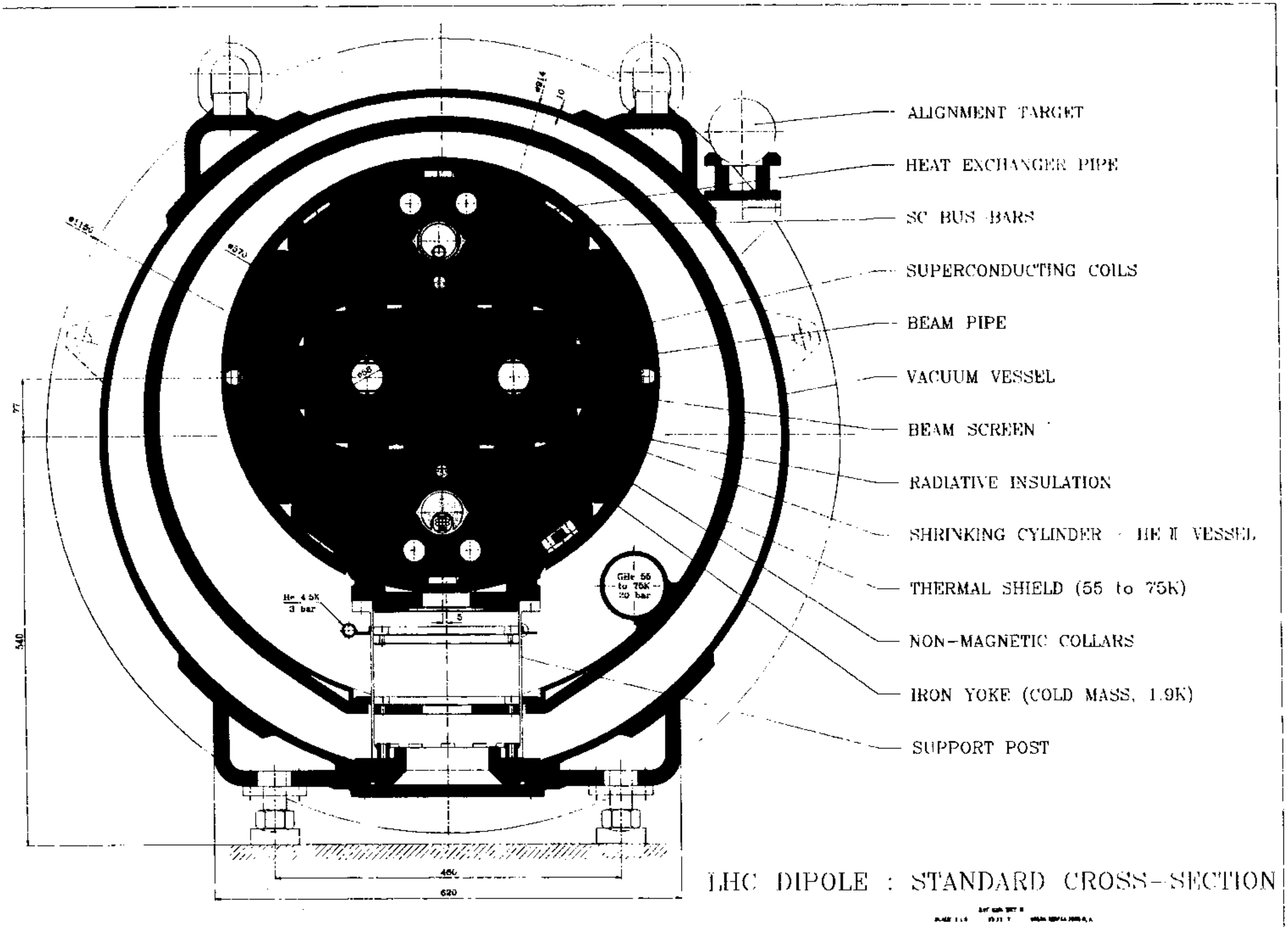
◆ *Magnet Options for VLHC*

- ***Moderate-field magnets*** *($4\ T < B < 9\ T$)*

  Uses $\cos(\theta)$ NbTi magnets.
  - Magnet and machine are well understood
  - Fermilab is doing this R&D via LHC quadrupole program

  Little synch. radiation damping except at high end
  - High-field NbTi magnets are hard to make
  - Needs expensive 1.8 K cryogenics for $B > 7$ T

- Not actively being pursued for VLHC



LHC DIPOLE : STANDARD CROSS-SECTION

Magnet Options for VLHC

- *Very-high-field magnets* ($B > 12$ T)
  - oodles of synchrotron radiation damping
  - too much synchrotron radiation power!
  - limited design options for magnets

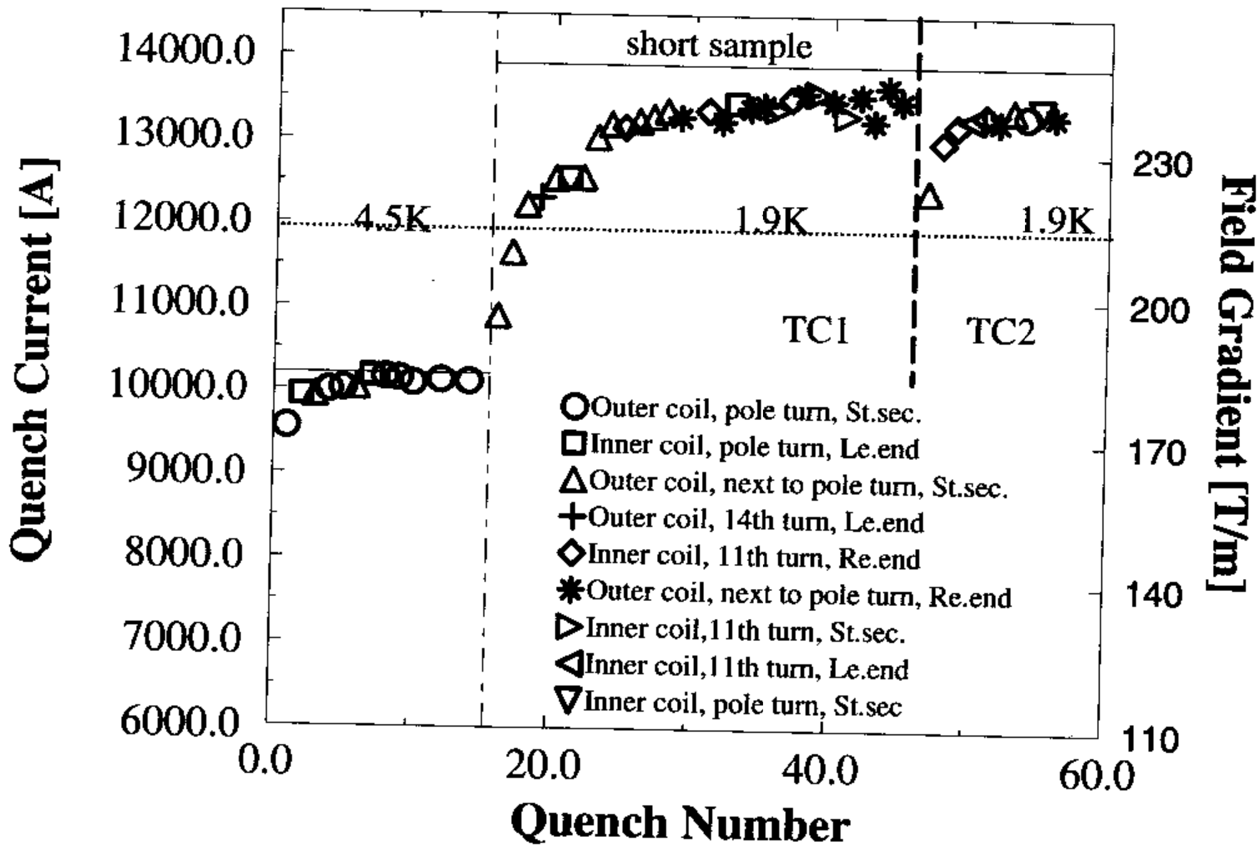
  Neither cos(θ) nor NbTi are possible
  Forces are huge

- Conclusion: Very high field is not worth the effort

  Only a small decrease in circumference
  Additional emittance damping is not needed
  Too much synchrotron radiation
  Magnets will be much more costly

HTS ? Who knows?
Some interesting progress lately – 1 kA cable
A moderate effort keeps us connected

III. Model Magnet Program



◆ *Magnet Options for VLHC*

- ***High-field magnets*** *($\sim$9 T < B $\leq$ 12 T)*
  - lots of synchrotron radiation damping
  - accelerator physics issues are understood (?)
  - numerous design options for magnets

    Cos(θ) NbTi at 1.8 K for B < 10 T
      Material is well understood, available and sort of cheap.
      Requires very high mechanical and material tolerances

    Cos(θ) Nb_3Sn (Al?) at 4.5 K for B$\leq$12 T
      Material needs R&D to improve performance and reduce cost
      Mechanical and material tolerances are relaxed relative to NbTi
      Cos(θ), horizontal 2-in-1 uses the least superconductor and steel

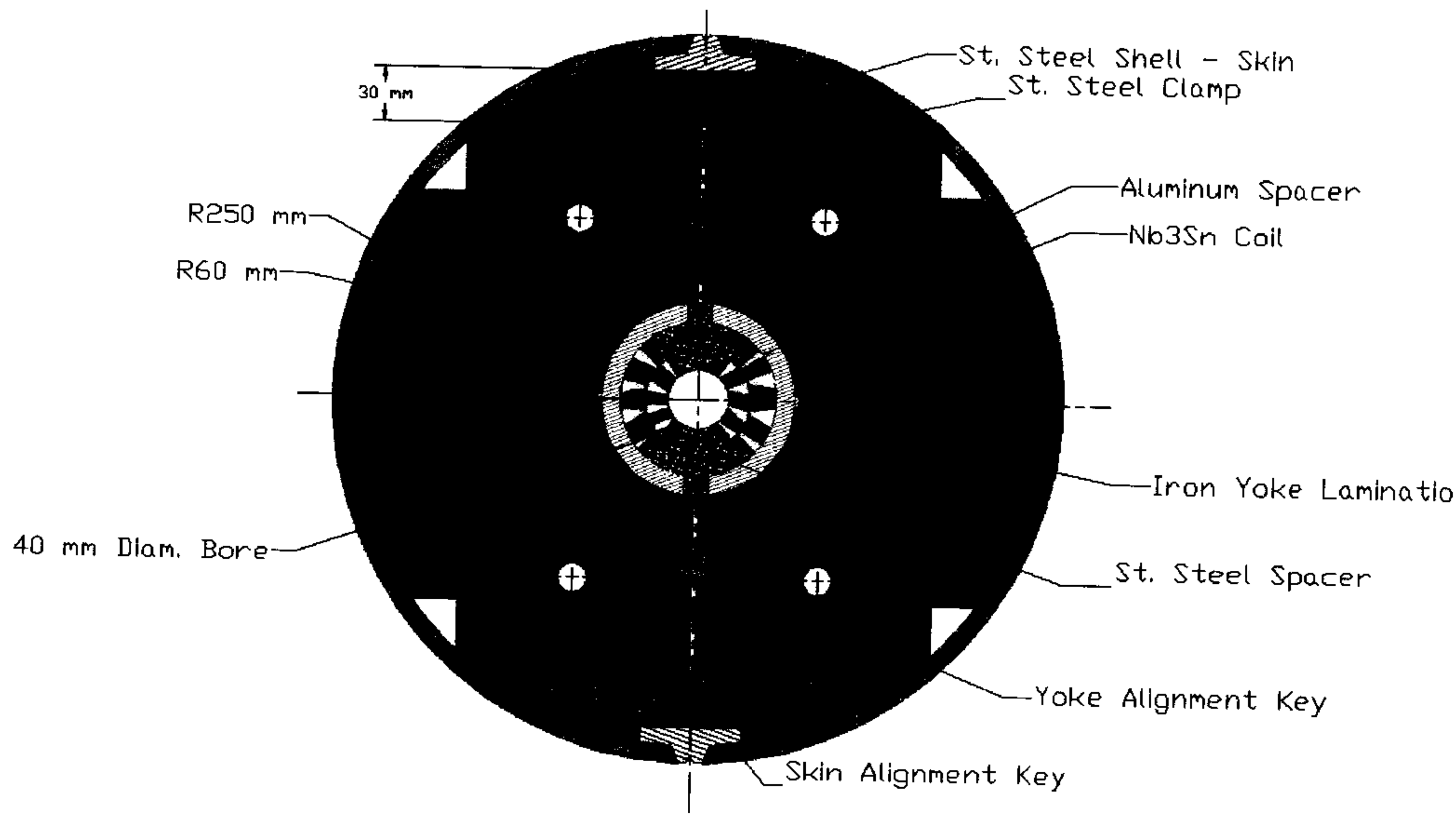
    Block designs Nb_3Sn (Al?) for B > 10 T
      There is a very promising concept — common coil 2-in-1
        May have simple assembly options, small aperture

◆ VLHC R&D GOALS

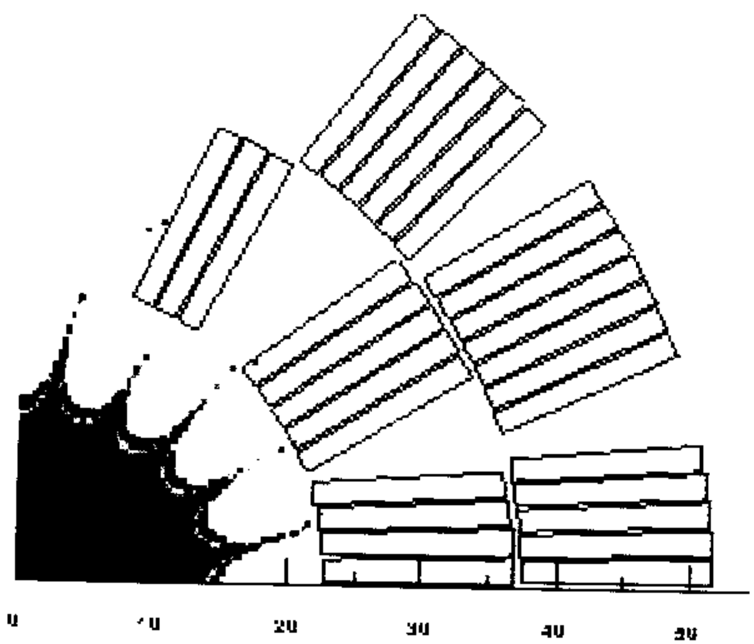
- *To design the machine and answer the accelerator physics questions*
- *To develop the magnets*
- *To reduce the cost, particularly of the magnets and tunnels*
- *To help find the answers needed to make an informed decision about the next collider*

VLHC R&D PLAN

- *The major technical issue is the performance and cost of the magnets. What's the Fermilab high-field plan?*
  - Concentrate on magnets…
    - One effort on a "traditional" Nb3Sn magnet
      Cos(θ), 10 T – 11 T, initially single aperture, eventually horizontal 2-in-1
    - Another effort on a "speculative" Nb3Sn magnet that holds the promise of major cost reduction.
      Two-in-one common planar coils, small aperture, 10 T – 11 T.
  - And materials
    - A national R&D program to improve the performance (Jc, deff, reaction time and temperature, strain resistance…) of A-15 conductors
    - Coupled with a national R&D program to increase the scale and reduce the cost of A-15 production.


30 mm
St. Steel Shell - Skin
St. Steel Clamp
Aluminum Spacer
Nb3Sn Coil
R250 mm
R60 mm
Iron Yoke Laminatior
40 mm Diam. Bore
St. Steel Spacer
Yoke Alignment Key
Skin Alignment Key

Magnetic Design

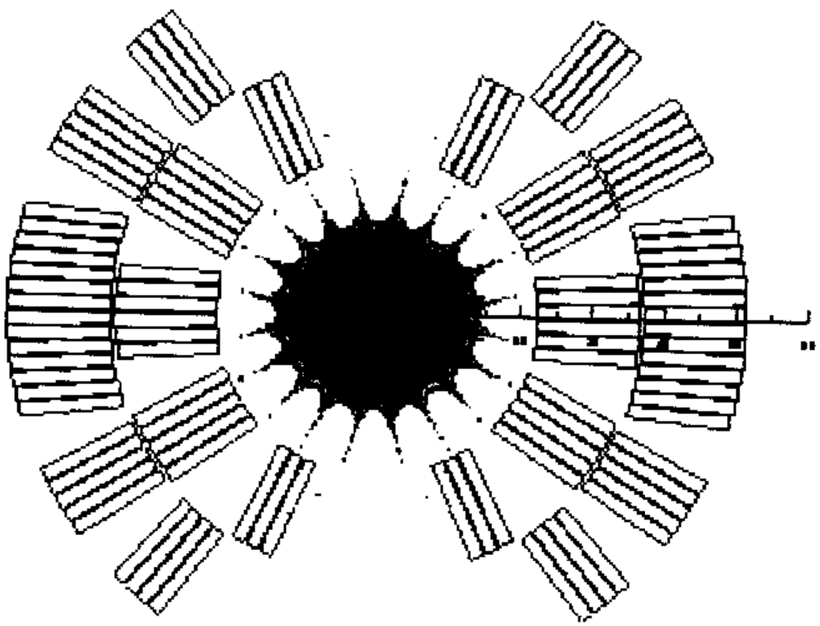


Design parameters

Magnet bore, mm	50	45	40
Number of blocks	3+3	3+3	3+3
Number of turns	2x32	2x30	2x26
Iron ID, mm	127	121	120
Bo/I, T/kA	0.7593	0.7407	0.6775
Bss, T	12.4	12.4	12.5
Iss, kA	16.8	16.8	18.5
I(11 T), kA	14.5	14.9	16.2
W(11 T), kJ/m	289	256	221
L, mH/m	2.75	2.32	1.67

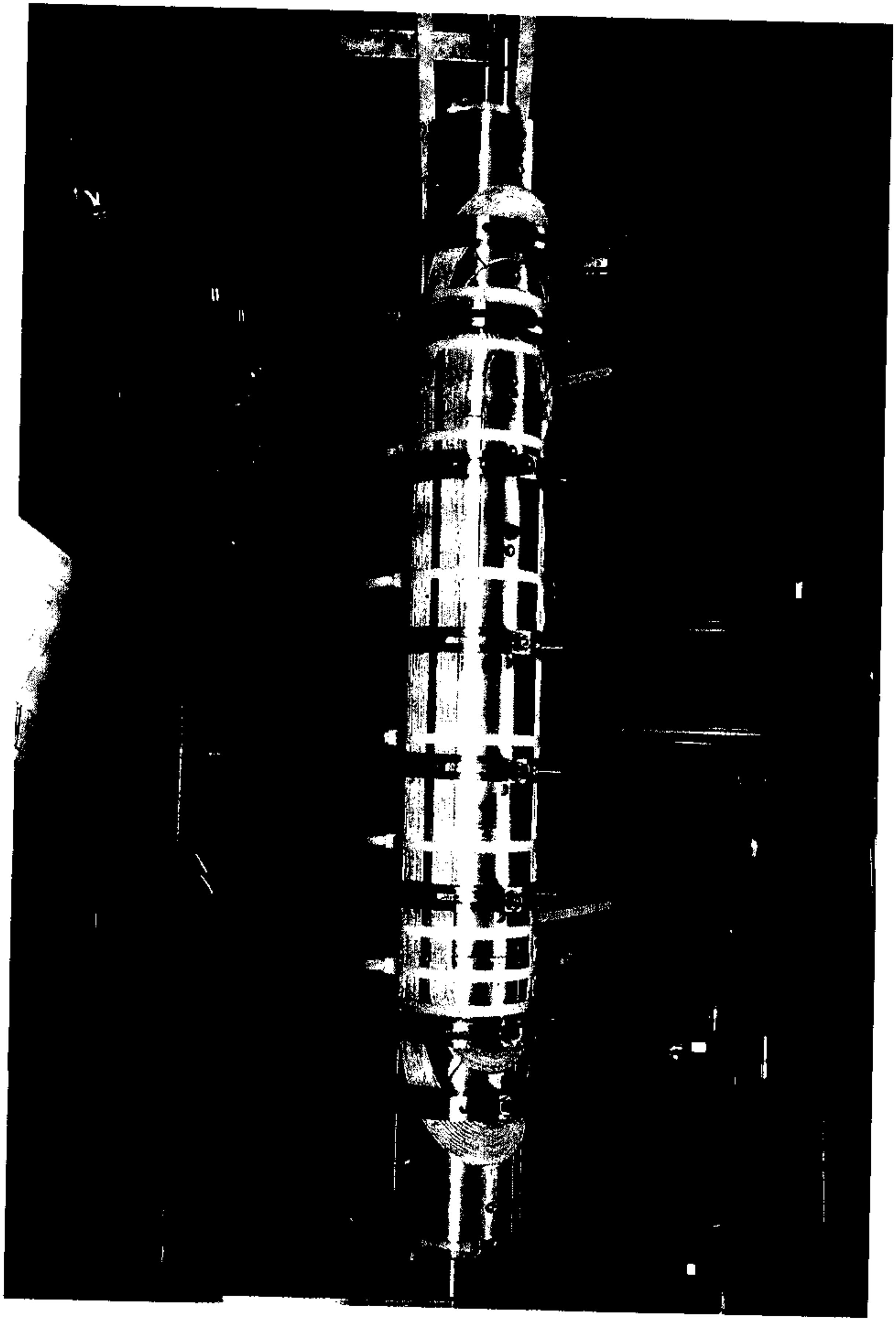
Fermilab High Field Magnet R&D

Magnetic Design



Magnet design parameters

Magnet bore diameter,mm	44.5
Maximum central field,T	12.28
Short sample limit, kA	18.14
Central field transfer function, T/kA	0.7407
Coil current @ 11 T central field,kA	16.25
Stored energy @ 11 T, kJ/m	252
Magnet inductance, mH/m	1.91
Coil area, mm^2	2512

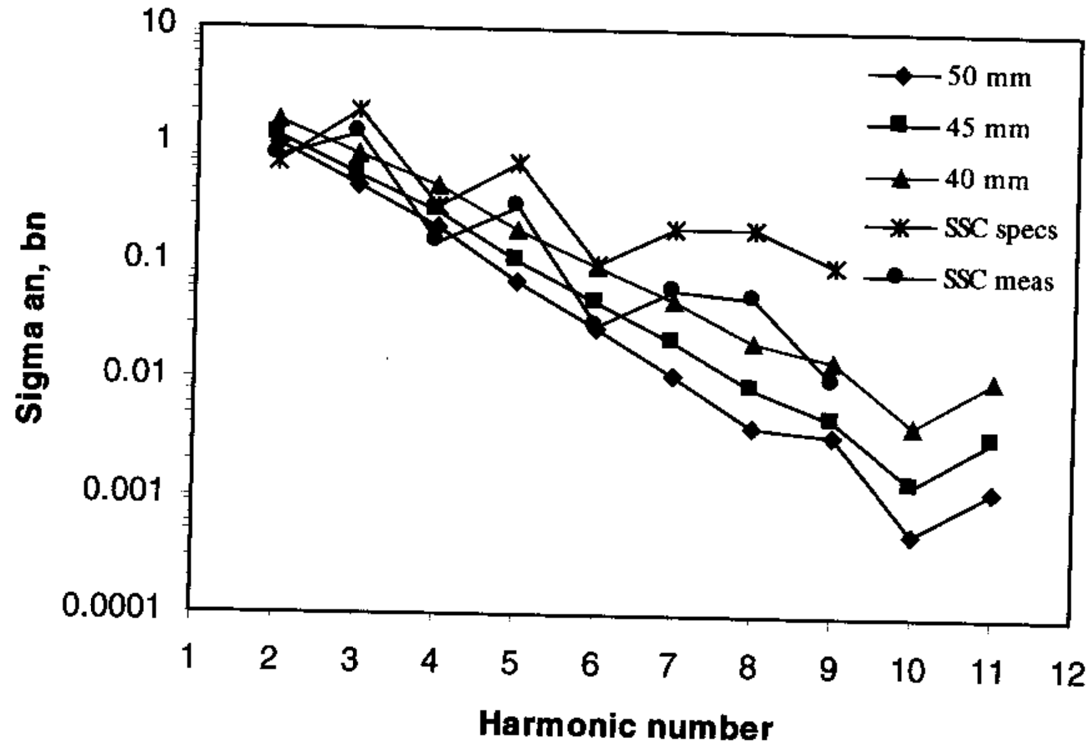


Geometrical Harmonics

Field harmonics @ 1 cm (unit)

n	bn
3	-0.000
5	0.000
7	-0.007
9	-0.071
11	0.103

Harmonics RMS

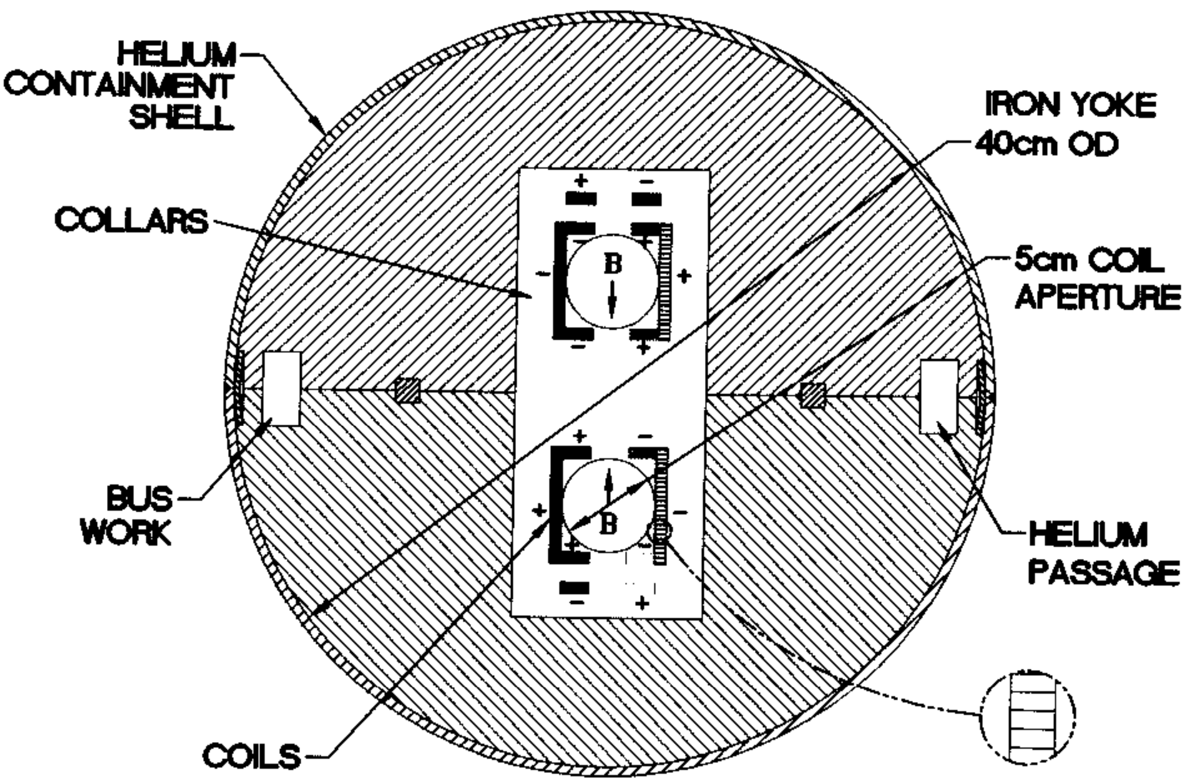


Coil cross-section area comparison

Magnet	45mm	CERN	MSUT	LBNL
Bmax, T	12.3	10	11.5	13
Cu/Sc	0.85	0.38	1.27	0.4/1.15
Coil area, mm^2	2512	3944	4705	6790

HIGH FIELD (10T-15T) TWIN APERTURE SUPERCONDUCTING DIPOLE

COMMON COIL DESIGN

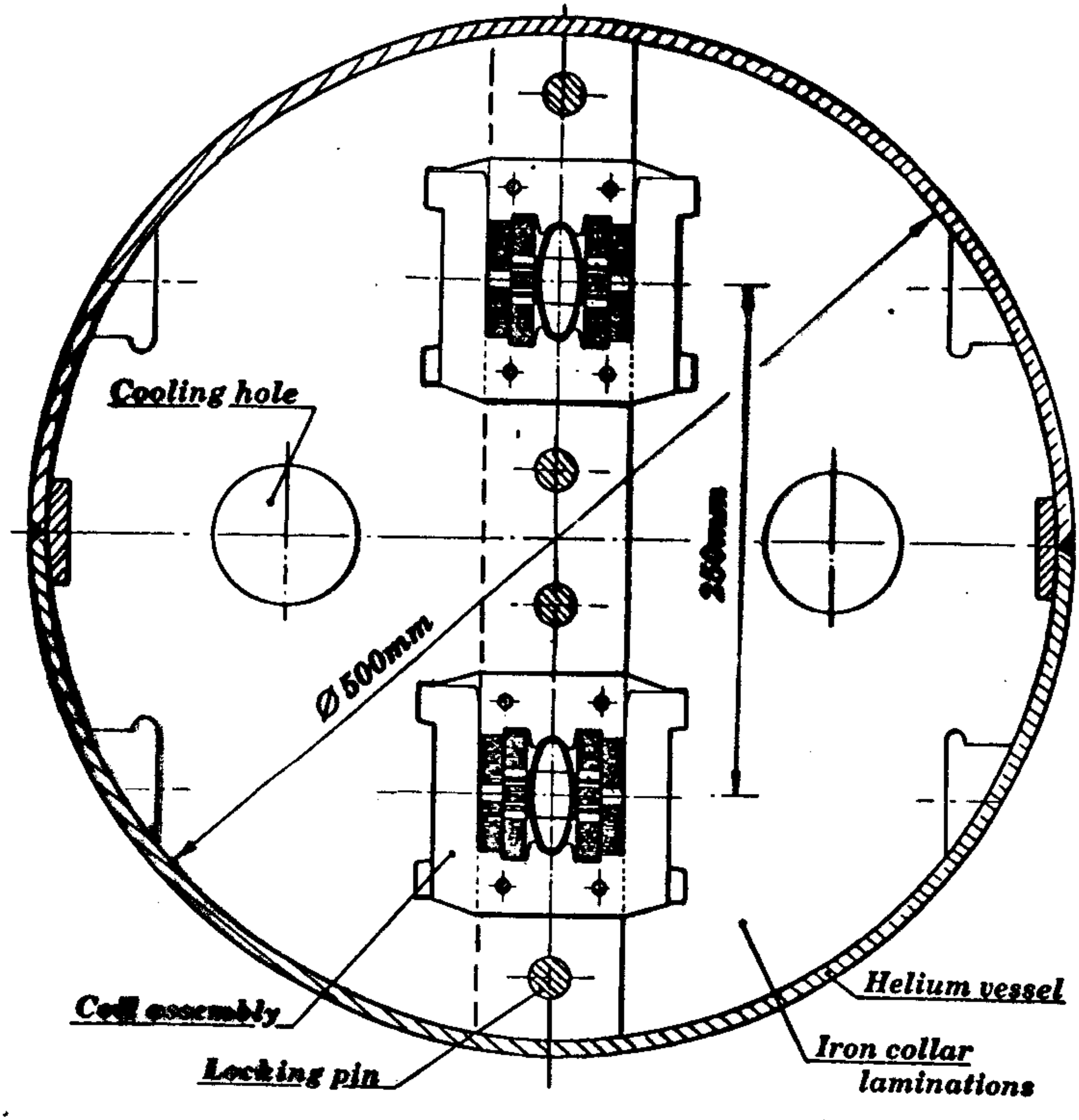


COLD MASS CROSS-SECTION

SCALE 1/4

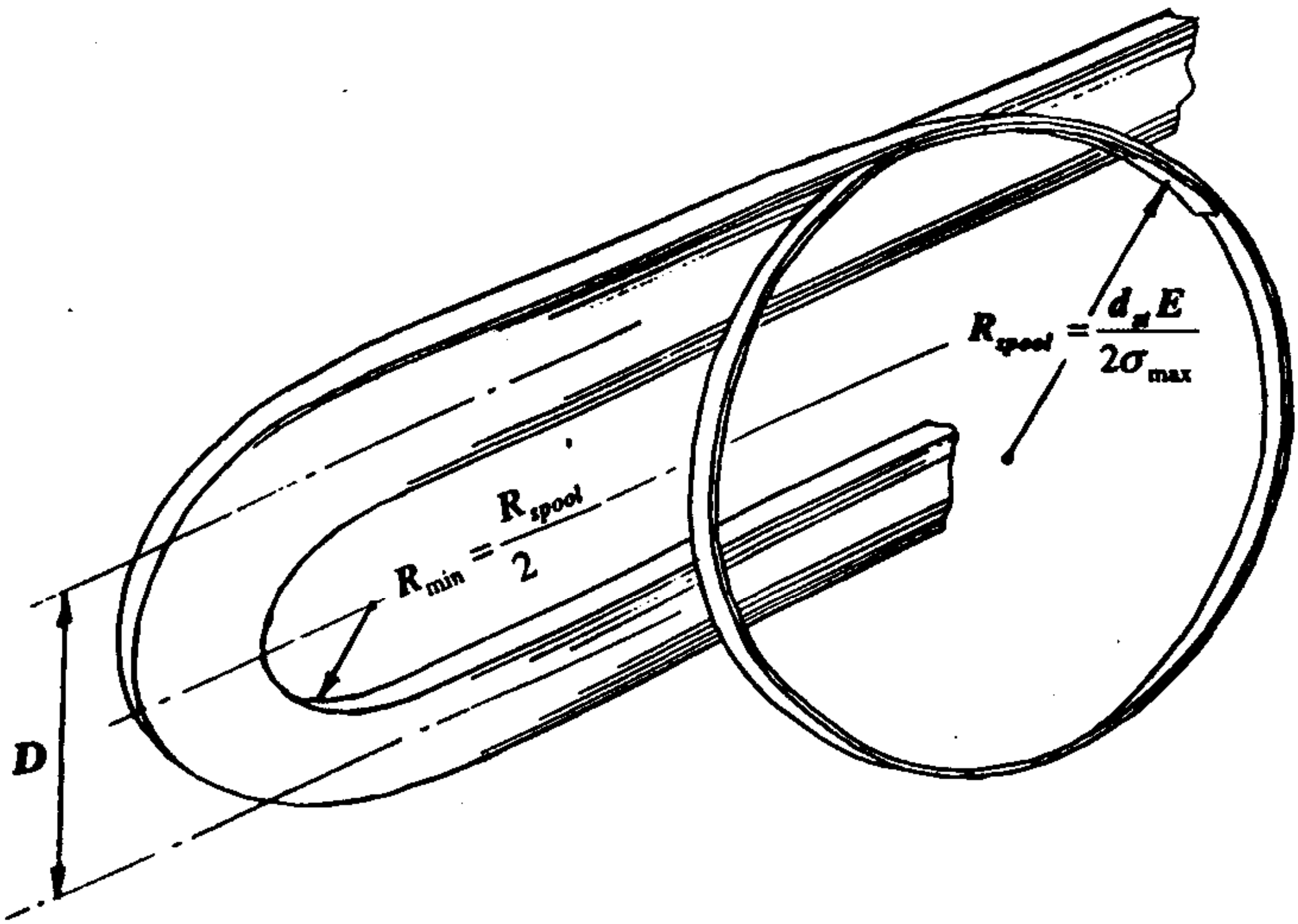
Common Coil & Block Type Design

Cross – section of double aperture dipole



React & Wind Coil Technology

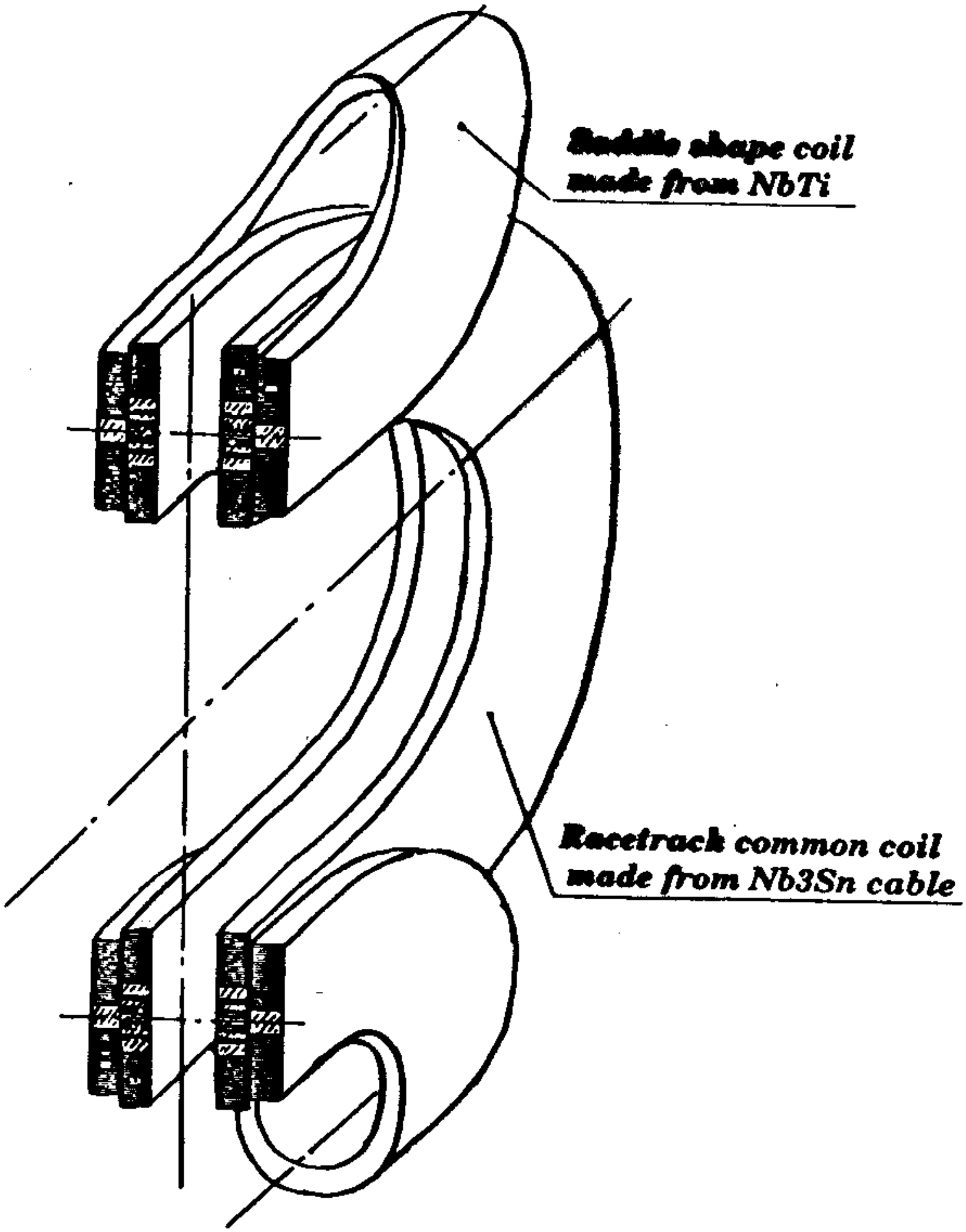
- an opportunity for the common coil design



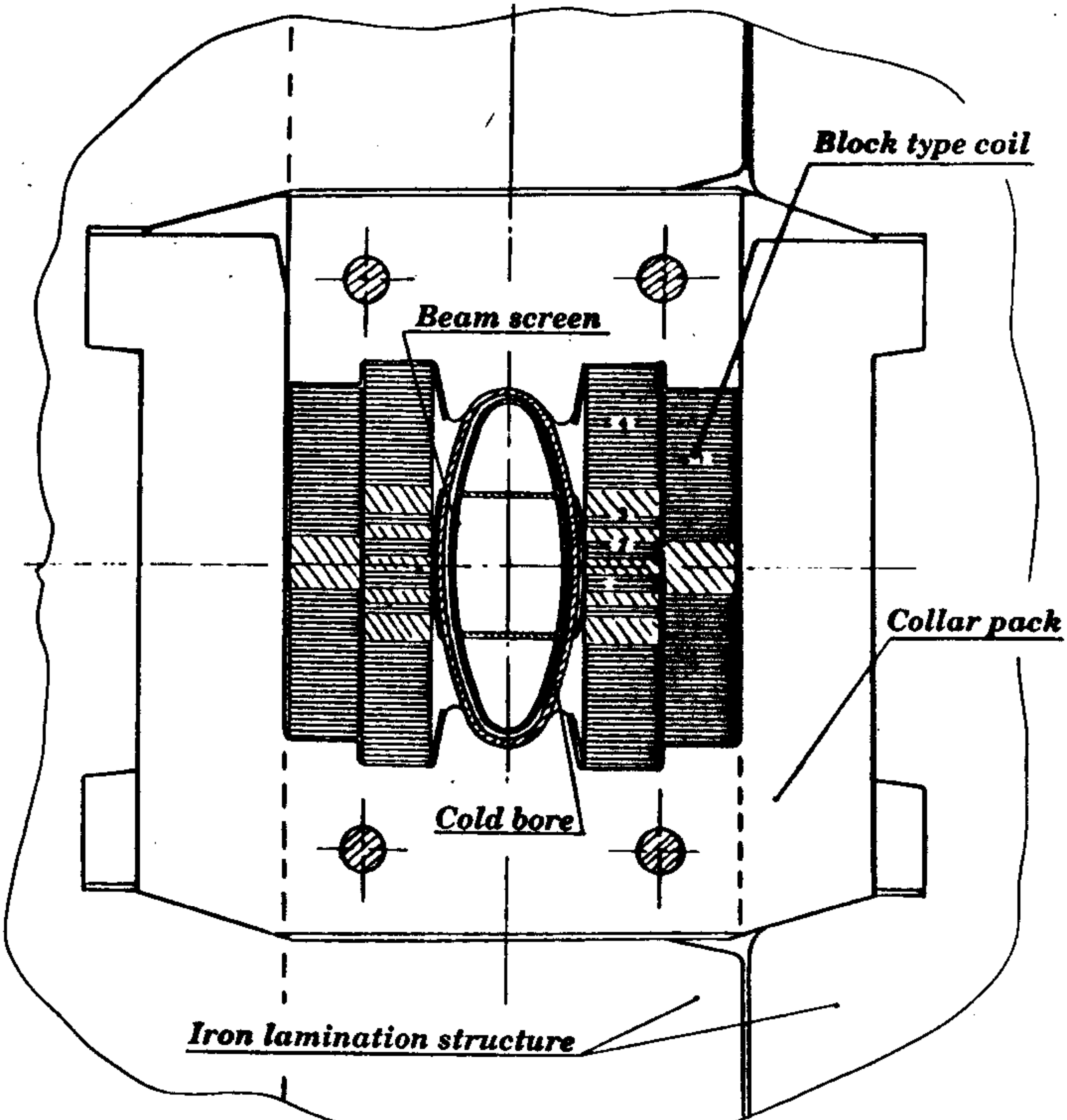
For example: σ_{max} ***= 150 MPa, - stress inside strand***
d_{str} ***= 0.5 mm - strand diameter***
E=100 GPa – Young modulus

R_{spool} ***= 170 mm &*** R_{min} ***= 85 mm***
D ~ 250 mm - distance between beams

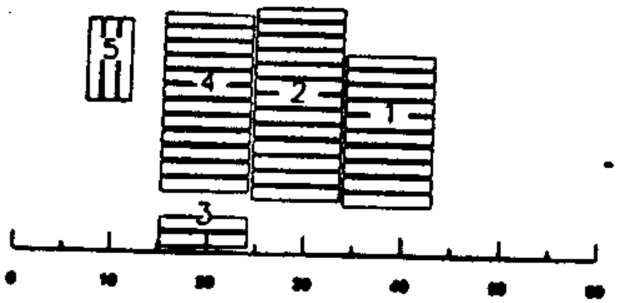
Coil End Design for Hybrid Magnet



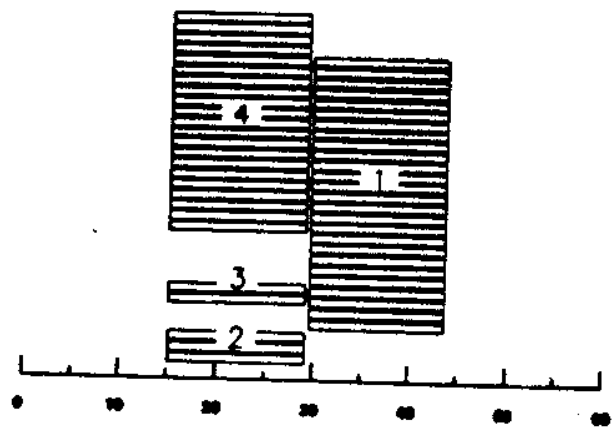
Coil Assembly Cross-section



Block-type design: coil cross-section



a) with auxiliary coil



b) without auxiliary coil
(~ 30% more conductor volume)

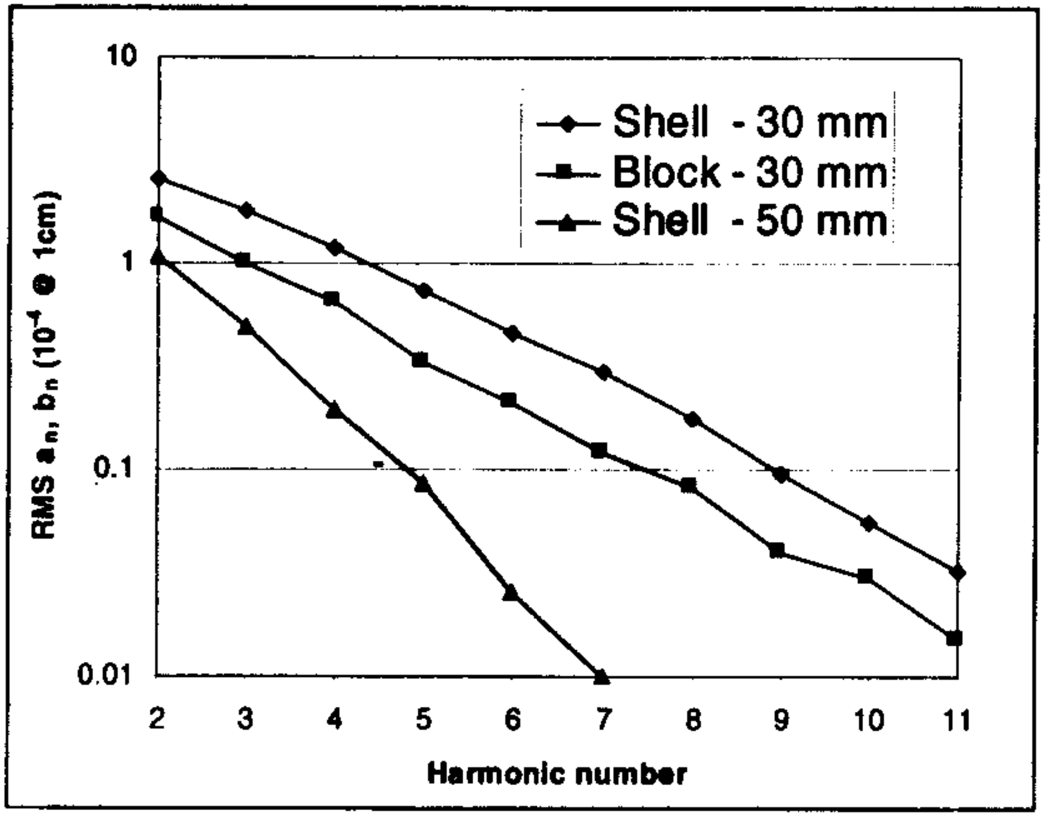
Geometric harmonics

10^{-4} @ 1cm

30 mm 30 mm

Component	Shell	Block	50 mm Shell
b_3	0.1	-0.1	0.0
b_5	0.3	0.3	-0.1
b_7	- 0.7	0.6	0.0
b_9	0.6	-0.8	0.1
b_{11}	2.9	1.2	0.0
b_{13}	-0.5	0.2	0.0

Random errors



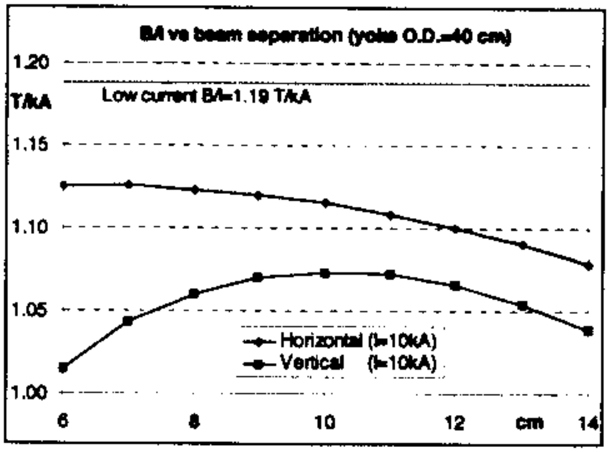
- No longitudinal averaging

- Magnetic measurements?

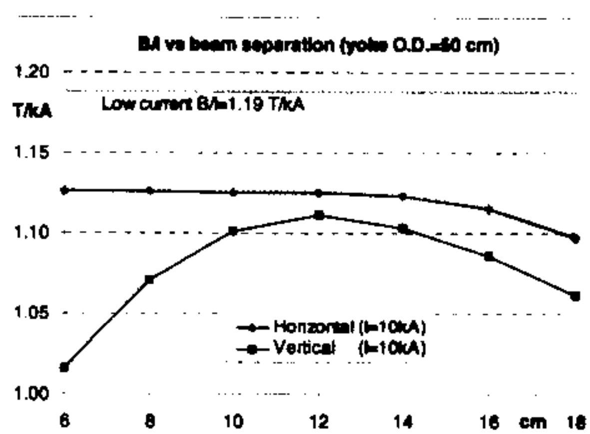
Energy and forces

Parameter	Unit	Shell	Block	50 mm
Operating current	kA	10.2	10.1	16.7
Stored energy	MJ/m	0.35	0.41	0.73
Inductance	mH/m	6.7	8.0	5.2
$-\Sigma F_y$ (1 quadrant)	MN/m	0.9	0.8	1.2
ΣF_x (1 quadrant)	MN/m	2.0	2.3	3.1
Stress (Φ/y, 1st layer)	MPa	86	28	100
Stress (Φ/y, 2nd layer)	MPa	84	36	75

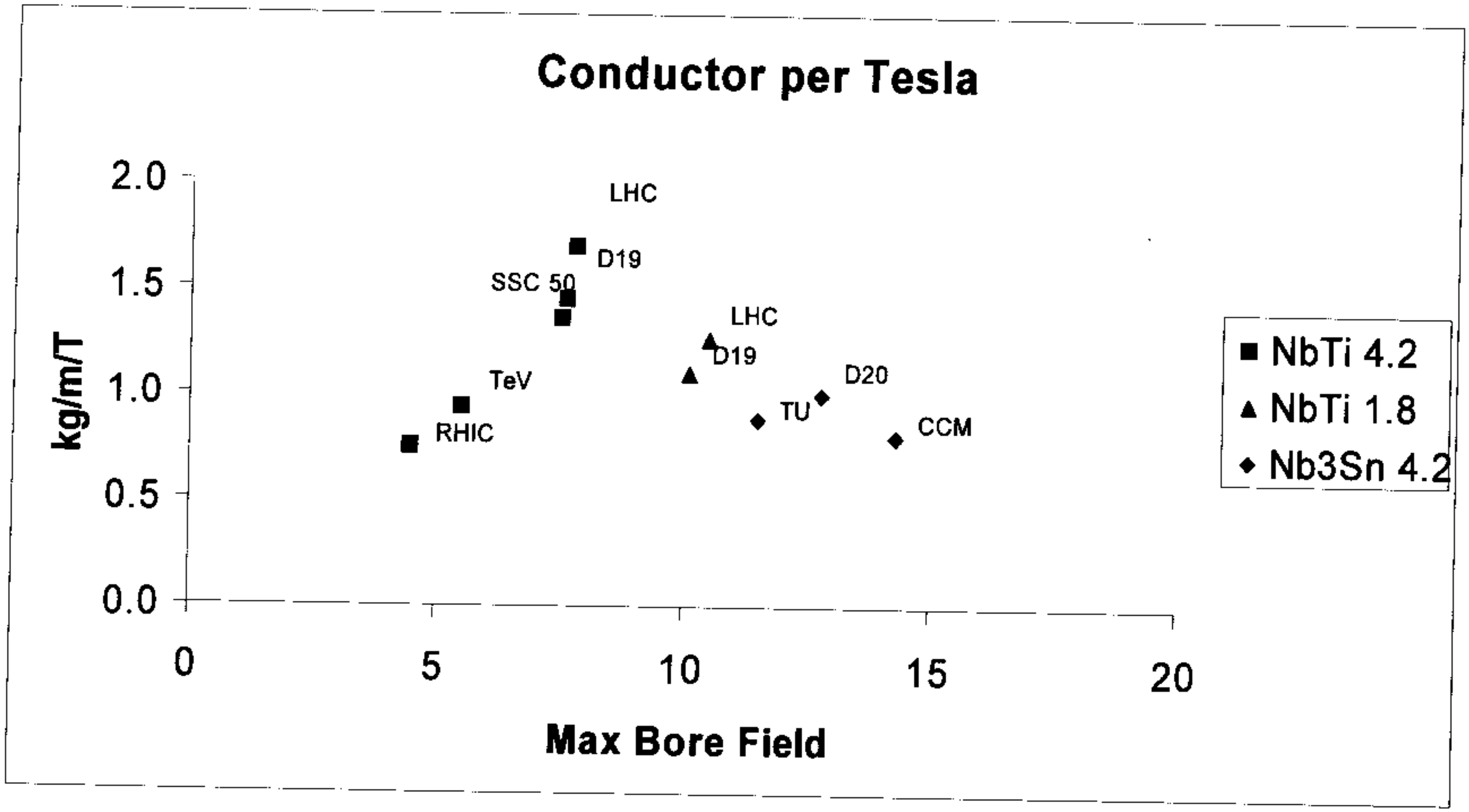
Transfer function for 40 cm yoke diameter



Transfer function for 50 cm yoke diameter



Magnets for a Very Large Hadron Collider
Port Jefferson, November 16-18, 1998
http://www.fnal.gov/projects/hgq/hfm/ws_bal/viewgraphs.html
G. Sabbi
Magnetic design of small-aperture dipoles


Conductor per Tesla
kg/m/T
2.0
1.5
1.0
0.5
0.0
0
5
10
15
20
Max Bore Field
LHC
D19
SSC 50
TeV
RHIC
LHC
D19
D20
TU
CCM
NbTi 4.2
NbTi 1.8
Nb3Sn 4.2

Conclusions

- 30 mm bore dipole with 12-13 T design field using Nb3Sn conductor at 4.2 K allows substantial savings in superconductor wrt 50 mm bore magnet with same design parameters.
- For these design parameters, shell and block design are substantially equivalent in terms of conductor efficiency and field quality.
- Vertical arrangement of the two apertures requires 50% larger yoke radius wrt horizontal arrangement in order to achieve same transfer function.

VLHC R&D PLAN

- *What does such a plan cost?*

U.S. HEP Superconducting Magnet and Materials R&D (K$)

Fiscal Year	**1998**	**1999**	**2000**	**2001**
High-field magnet R&D at LBNL	$2150	$2200	$2300	$3000
High-field magnet R&D at BNL	500	750	900	1500
High-field magnet R&D at Fermilab	700	1500	2700	3500
Superferric R&D at Fermilab	425	1100	1500	2000
Texas A&M University	345	350	500	700
Materials R&D in industry and universities*	200	400	600	2000
Total (not including G&A)	**$4320**	**$6300**	**$8500**	**$12700**

* This line is the sum of SC materials R&D in industry and universities funded by FNAL and LBNL in roughly equal amounts through FY2000. In FY2001 this is assumed to be separately funded.

◆ VLHC R&D PLAN (continued)

- *The materials R&D needs to increase after FY2002 to scale up production to study cost reduction possibilities.*

- *Other issues, like accelerator design and experimentation, and tunneling R&D need to be added.*

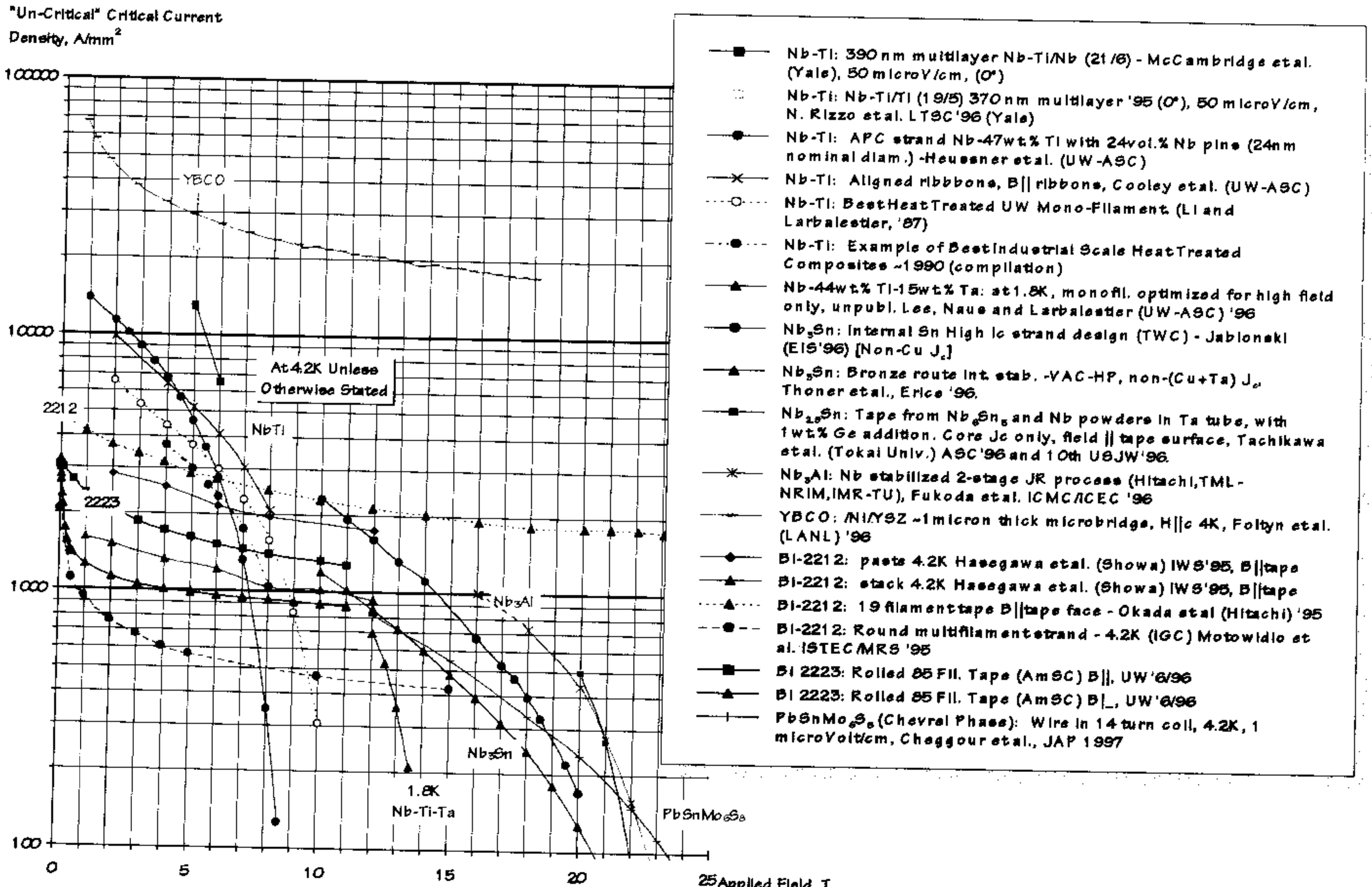
- *Don't forget overhead!*

The R&D cost grows to about $20 million per year until one either starts building another accelerator, or decides to build a VLHC.

◆ New and improved materials

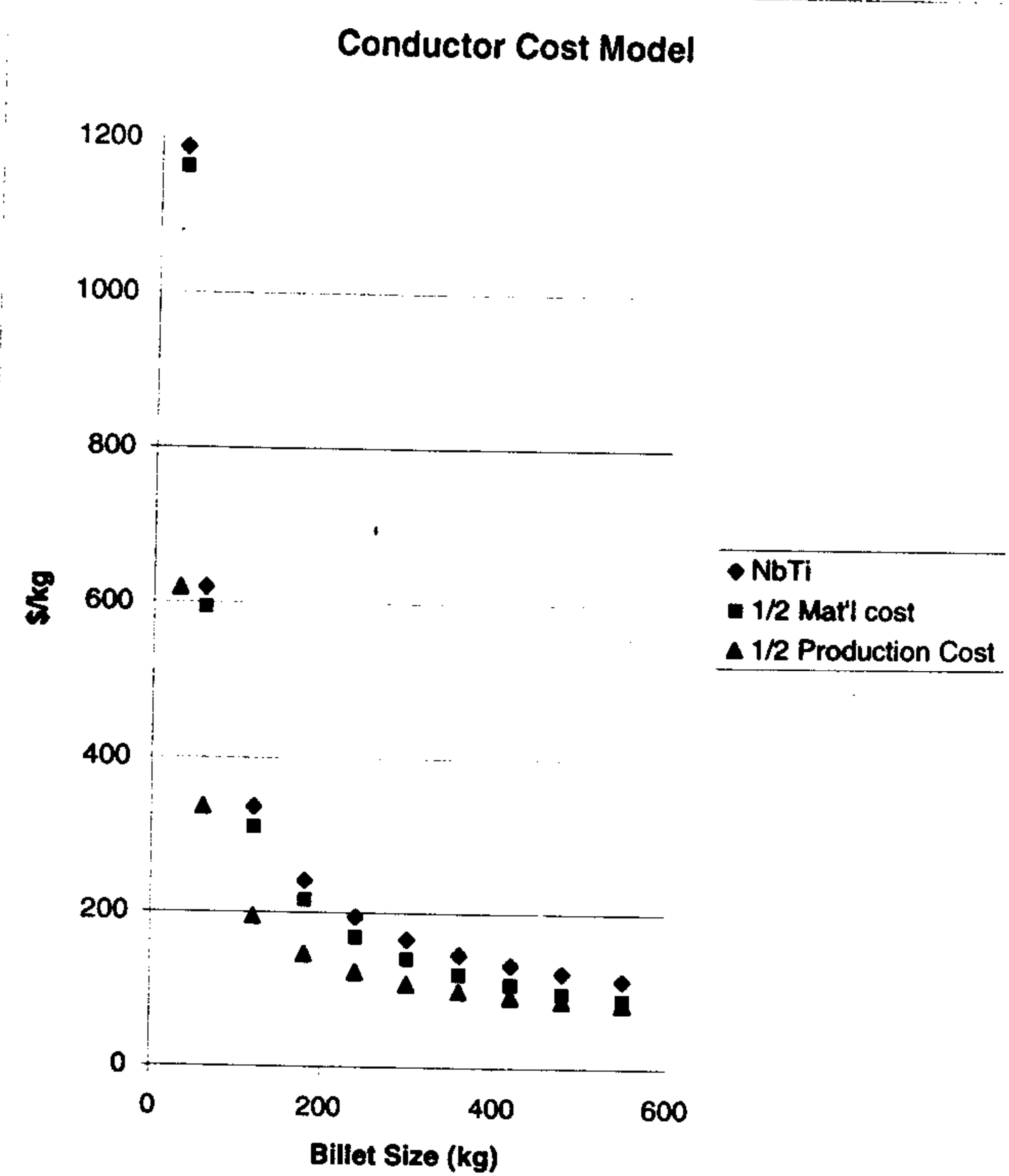
- ITER (✝ now dead ✝) inspired much progress in Nb3Sn and Nb3Al, doubling Jc at high field, reducing AC losses, lowering cost.
- Large factors in Jc and cost are still possible, but the market promise has disappeared.
- We are trying to start a national R&D effort in Nb3Sn and Nb3Al R&D through the DOE and national labs. We asked for $2M per year, starting in FY2000, increasing to ~$4M per year in FY2003.
  - Better Jc performance means smaller apertures and less superconductor
  - Smaller filament diameter means better injection field
  - Shorter and lower-temperature heat treatments mean cheaper fabrication
- **Scaling to large production runs means big cost reductions**

Advancing Critical Currents in Superconductors

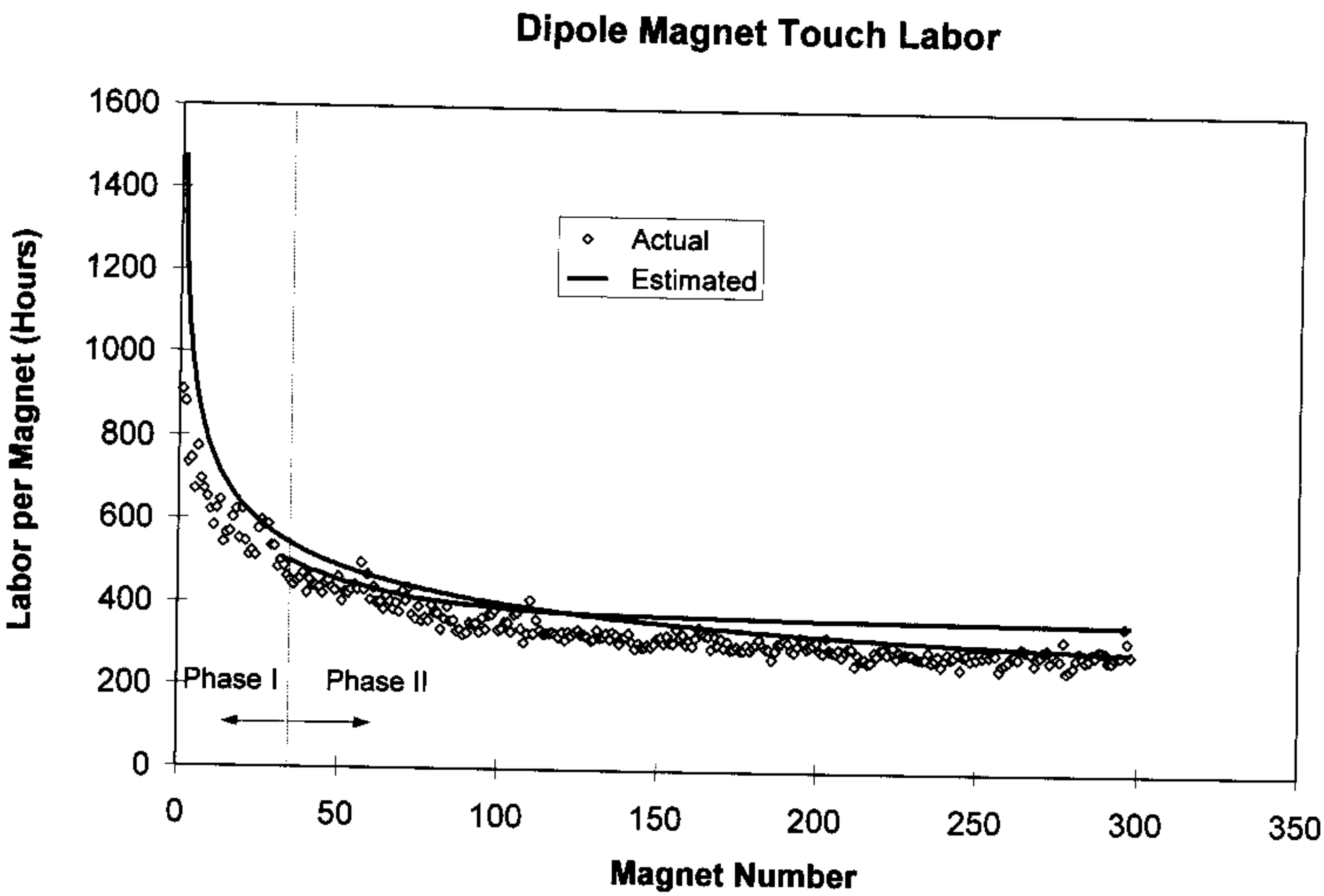


University of Wisconsin-Madison
Applied Superconductivity Center

November 3rd 1997 - Compiled by Peter J. Lee - BestInClass.ppt, JCProg40.xls



Conductor Cost Model
1200
1000
800
600
400
200
0
$/kg
0
200
400
600
Billet Size (kg)
NbTi
1/2 Mat'l cost
1/2 Production Cost


Dipole Magnet Touch Labor
Labor per Magnet (Hours)
1600
1400
1200
1000
800
600
400
200
0
Actual
Estimated
Phase I
Phase II
0
50
100
150
200
250
300
350
Magnet Number

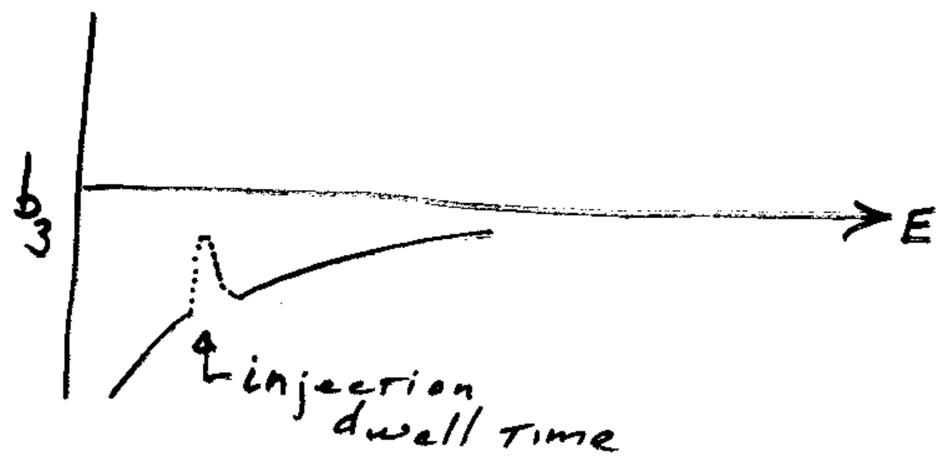
F:\cost.doc

◆ What about accelerator design?

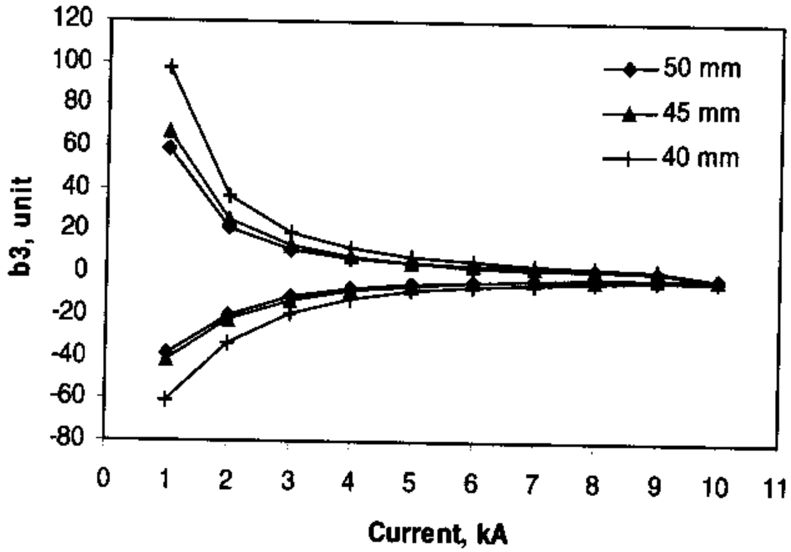
✶ Influence of magnetization on injection field

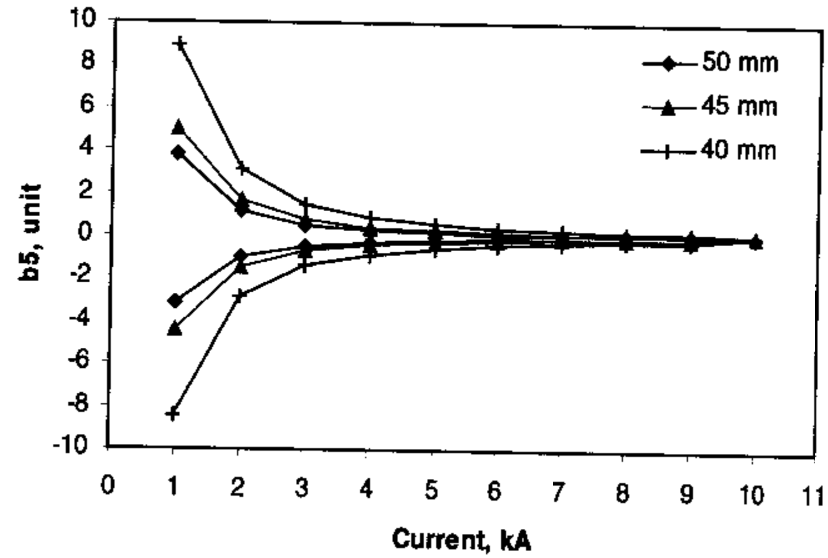
- The magnetization effects for Nb3Sn might be worse than for NbTi, due to higher Jc and effective filament diameter (d_{eff})at injection.

- The real problem is not the sextupole and decapole fields, which can be corrected, but their time dependence and the "snap-back."



Coil Magnetization Effect





18 kA = 11 T = 50 TeV

Choosing the injector energy

- The HEB injector was chosen at 3 TeV at Snowmass_96
  - Based on highest-energy HEB that we thought could be filled by the 150 GeV Main Injector
- Higher energy would be better
  - Could have ~ 4 TeV on site with 7 T SSC-type magnets at 4 K
  - Why stay on the site? Could go slightly larger for higher energy
  - But, an E > 3 TeV injector would be hard to fill from 150 GeV Main Injector.
  - Could build a simple, <u>conventional</u> "Energy Doubler" in the Main Ring tunnel after the Tevatron shuts off. Much of the infrastructure still exists for a 150 Gev to 300 GeV accelerator. This would inject into 5 TeV HEB.
  - If this 5 TeV booster were low-field (superferric), its circumference would be about 50 km, and could fill the Collider Ring in two or three cycles, reducing the injection dwell time.

◆ A VLHC Organization in the U.S.

- ## There is a U.S. national VLHC organization.
  - Representatives of BNL, Fermilab, LBNL met at Fermilab in February, 1998 to discuss the form of a VLHC R&D organization in response to the Gilman Subpanel recommendation:

"The Subpanel recommends an expanded program of R&D on cost reduction strategies, enabling technologies, and accelerator physics issues for a VLHC. These efforts should be coordinated across laboratory and university groups with the aim of identifying design concepts for an economically and technically viable facility."

  - John Peoples asked the Directors of the BNL, LBNL and Cornell to appoint members of a VLHC Steering Committee.

BNL members:	Mike Harrison, Stephen Peggs
Cornell Member:	Gerry Dugan
Fermilab Members:	Peter Limon, Ernie Malamud (Secretary)
LBNL Members:	**Bill Barletta, Jim Siegrist**

◆ The VLHC Steering Committee

- **The Steering Committee met in April, 1998, endorsed the concept of <u>steering</u> and promptly created three Working Groups with convenors to do the <u>rowing</u> .**

  Magnet Technology
  Peter Wanderer (BNL), Bill Foster (FNAL), Ron Scanlan (LBNL)

  Accelerator Technology
  Chris Leehman (TJNAF), Waldo McKay (BNL), John Marriner (FNAL)

  Accelerator Physics
  Alan Jackson (LBNL), Shekhar Mishra (FNAL), Mike Syphers (LBNL)

- **Some ground-rules**
  - **Initially, the US site of the VLHC is assumed to be Fermilab.**
  - **Focus on the technology and cost reduction for VLHC accelerators.**

The VLHC Steering Committee

- ## General charge to the working groups

  Guided by the Snowmass-1996 parameter sets explore and develop innovative concepts that will result in significant cost reductions. Coordinate parameter sets and infrastructure requirements for the various options and designs with the other working groups.

  - The working groups are open to all. Participation is welcomed from all US and foreign institutions.
  - Organize workshops on the relevant issues in accelerator physics, magnet technologies, and accelerator technologies.
  - Publish the results and hold an annual meeting to inform the community and set agendas for the coming year.

◆ A National VLHC Organization

- Workshop on VLHC magnets
  - Port Jefferson, LI, NY; November 16 – 18, 1998
    Lead organizer: Peter Wanderer
- Workshop on accelerator technology
  - Thomas Jefferson Laboratory; February 8 – 11, 1999
    Lead organizer: John Marriner
- Workshop on accelerator physics
  - Lake Geneva, WI; February 22 - 25, 1999
    Lead organizer: Mike Syphers

● <u>Annual meeting</u>

Monterey, CA; June 28 - 30, 1999

Organizers: Bill Barletta, Jim Siegrist

Does accelerator-based HEP have a future?

- *Yes, but only through*

  Global Collaboration

- *We need to get serious: form a lab that is truly world-wide in scope.*
  - CERN is an example, but not a model.
- One-third of the world economy has not contributed proportionally to HEP.
  - They must be brought in as full partners.

◆ *Forming the world-wide collaboration*

- This is much harder than building an accelerator, but it must be done.
- We must put the politics, collaborations, cost sharing and public relations into place that will make the VLHC possible.

◆ Scaling the SSC to VLHC Energy

		SSC Base 1991 M$	Applicable to Fermilab 1991 M$	Scaled 1991 M$	
1.	**Technical Systems**	3095	2782	5640	
1.1	Accelerator Syst.	1107	903	1191	
1.2	Magnet Systems	1988	1879	4450	
2.	**Conventional Const.**	1073	950	1266	
3.	**Proj. Man. & Syst. Eng.**	49	49	80	
4.	**Accel & Mag. Dev.**	74	74	100	
5.	**Indirects**	199	199	314	
	Subtotal	4490	4054	7400	
	Escalation	1019		1700	
	Contingency (as-spent)	843		1365	
	Total Estimated Cost (TEC)	6351		10465	
	Escalation (3%/year, to 2000)			13650	**Aaargh!**

◆ Scaling the SSC to VLHC Energy

	SSC Base 1991 M$	Scaled 1991 M$
1.2 Magnet Systems	**1988**	**4450**
1.2.1 Management	27	60
1.2.2 HEB	178	276
1.2.3 Collider Ring	1610	4025
1.2.4 Interaction Regions (4)	135	70
1.2.5 Magnet Test Lab	29	29
1.2.6 Everything else	9	0
Escalation to FY2000		**5785**

Example: The cost of a 3 TeV HEB based on the SSC HEB

HEB Accel. Syst.	163	213
HEB Magnets	178	267
HEB Conv. Const.	74	111
Share of Support & Manage	40	57
Share of Accel & Mag Developm.	8	12
Total	**463**	**660**
Escalation to FY2000		**861**